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Aircraft Structures Technical Memorandum 491

DETERMINING STRESS COMPONENTS FROM THERMOELASTIC DATA - A THEORETICAL STUDY(U)

by

T.G.Ryall and A.K.Wong

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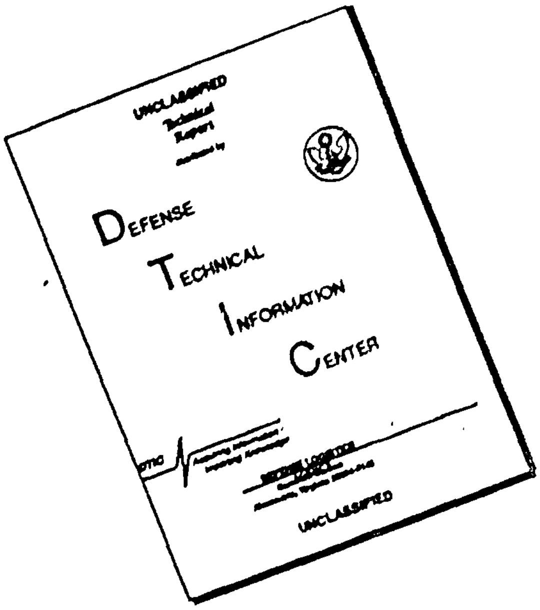

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AIRCRAFT STRUCTURES TECHNICAL MEMORANDUM 491

DETERMINING STRESS COMPONENTS FROM THERMOELASTIC DATA - A THEORETICAL STUDY

by

T.G. Ryall

A.K. Wong

SUMMARY

This paper presents a method for decomposing bulk stress data into individual stress components. This has applications in the field of thermoelastic stress analysis where the raw data are related only to the sum of the principal stresses (referred to as bulk stress). By considering equilibrium, and with some knowledge of the form of the solution and boundary conditions, it is shown that bulk stress data for a two dimensional body may be separated into stress components by mean of a least squares method.

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1. INTRODUCTION

Whilst the thermoelastic effect has been known for well over a century, it is only within recent years that this phenomenon has been exploited as a means of experimental stress analysis. Equipped with an infrared sensor, together with some precision scanning mechanisms and clever signal processing hardware, a system known as SPATE (Stress Pattern Analysis by measurement of Thermal Emission), can form a raster picture of the temperature fluctuation of body under cyclic loads. Since such thermal data are directly related to the changes in bulk stress ($\sigma_{xx} + \sigma_{yy} + \sigma_{zz}$), this system offers a powerful means of obtaining full-field non-contact measurements of stresses within structural components. As a result, the use of SPATE has become increasingly widespread, and many successful applications may be found in the literature (e.g., [1]-[3]). However, because temperature and bulk stress are scalar values, the vectorial nature of stress is lost from data obtained by such techniques. Whilst the bulk stress information may be useful for many qualitative inspection purposes, quantitative evaluations are possible only for cases where it is known that the stress field is dominant in one direction. Taking an extreme case as an example, it may be shown that SPATE would not be able to distinguish an unloaded body and one which is subjected to pure shear. The failure of SPATE to respond to pure shear was clearly shown in the experiment of Stanley and Chan [4].

Because the knowledge of individual stress components is important in many practical situations, much work has been done in the fields of holographic interferometry to separate principal stress components from isopachic and isochromatic fringe data (e.g. [5-7]). In thermoelastic stress analysis however, only the isopachic data may be obtained which, by themselves, do not provide enough information for determining the stress components. On the other hand, it is not true that the selection of stress values which satisfy a given set of isopachic data can be totally arbitrary. This is because the permissible stresses must satisfy equilibrium as well as known boundary conditions. It is shown in this paper that, at least for two-dimensional problems, the imposition of these conditions can be used to determine the stress components associated with a given set of isopachic data.

2. THEORY

For a two-dimensional isotropic material under elastic deformation in the absence of any body force, it is well known that the solution for stresses may be expressed in terms of a potential Φ, such that

$$\sigma_{xx} = \frac{\partial^2 \Phi}{\partial y^2}, \qquad \sigma_{yy} = \frac{\partial^2 \Phi}{\partial x^2}, \qquad \sigma_{xy} = -\frac{\partial^2 \Phi}{\partial x \partial y}. \tag{2.1}$$

where σ_{xx}, σ_{yy} and σ_{xy} are the normal and shear stress components, and Φ must satisfy the bi-harmonic equation

$$\frac{\partial^4 \Phi}{\partial x^4} + 2\frac{\partial^4 \Phi}{\partial x^2 \partial y^2} + \frac{\partial^4 \Phi}{\partial y^4} = 0. \tag{2.2}$$

For a simply connected body, the specification of two conditions of Φ around the boundary forms a well posed problem, and it may be shown that the necessary boundary conditions for Φ may be determined from two known components of stress at each point along the boundary. In such a case, the stress field may be uniquely determined, and there is thus no need for additional data. However, accurate boundary conditions may be unknown in many real situations, and the analyst is forced to resort to simplifications which may or may not be realistic. The assumption of a uniformly distributed stress profile across the boundary of a component under consideration is one such example. With the availability of other stress related information, such as experimentally obtained bulk stress data, the requirement for a complete set of the boundary conditions may be relaxed. The problem now becomes one which involves finding a solution to eqn (2.2) subject to certain known boundary conditions (e.g., making use of free boundaries) and its nearness to the bulk stress data.

As an illustration, consider a rectangular segment of a specimen bounded by $0 \le x \le \ell$, and $-0.5 \le y \le 0.5$. Let the sides $y = \pm 0.5$ be free edges and the remaining two boundaries be loaded by normal stresses which may be functions of y. Without loss of generality, considering only the symmetrical (about the x-axis) case, the analytical solution for Φ may be found in Timoshenko and Goodier [8], viz.,

$$\Phi = a_o \frac{y^2}{2} + a e^{-2\gamma x}\left(-\gamma \tan \gamma \cos 2\gamma y + 2\gamma y \sin 2\gamma y\right). \tag{2.3}$$

in which a_o and a are real coefficients, and γ satisfies the equation

$$\sin 2\gamma + 2\gamma = 0. \tag{2.4}$$

The non-trivial roots of eqn (2.4) are complex, and appear in conjugate pairs. Also, if γ is a root, so is $-\gamma$. For simplicity, let us further assume that the stresses are known to be uniformly distributed as $x \to \infty$ so that only values of γ which have positive real parts need be considered. For the stresses to be real, the general expression for Φ may be written as

$$\begin{aligned}\Phi = a_o \frac{y^2}{2} &+ \sum_{k=1}^{\infty} a_k e^{-2\gamma_k x} \left(-\gamma_k \tan \gamma_k \cos 2\gamma_k y + 2\gamma_k y \sin 2\gamma_k y\right) \\ &+ \sum_{k=1}^{\infty} \overline{a}_k e^{-2\overline{\gamma}_k x} \left(-\overline{\gamma}_k \tan \overline{\gamma}_k \cos 2\overline{\gamma}_k y + 2\overline{\gamma}_k y \sin 2\overline{\gamma}_k y\right),\end{aligned} \tag{2.5}$$

where $\overline{a}_k$ and $\overline{\gamma}_k$ are the conjugates of a_k and γ_k respectively.

The expressions for the stress components may be obtained by direct differentiation of eqn (2.5) and it may be shown that the bulk stress S is given by

$$\begin{aligned}S &= \sigma_{xx} + \sigma_{yy} \\ &= a_o + 8 \sum_{k=1}^{\infty} \gamma_k^2 a_k e^{-2\gamma_k x} \cos 2\gamma_k y + 8 \sum_{k=1}^{\infty} \overline{\gamma}_k^2 \overline{a}_k e^{-2\overline{\gamma}_k x} \cos 2\overline{\gamma}_k y.\end{aligned} \tag{2.6}$$

In general, the coefficients a_k would be dependent on the distribution of σ_{xx} and σ_{xy} at $x = 0$. However, suppose that this stress distribution is not known *a priori*, but experimental data on bulk stresses, such as those obtained from SPATE, are available. The problem of determining individual stress components for this example then essentially involves the determination of the coefficients a_k (and also the number of a_k's to sufficiently represent the solution) in eqn (2.5) subject to some best-fit criterion such that the difference between S and the array of experimentally observed bulk stresses S^E is minimised.

3. TEST CASES

To test the viability of the proposed scheme, the stress field was first solved directly for the case where a known distribution of stresses at the boundary $x = 0$ is applied. The bulk stresses at discrete points on a $N_x \times N_y$ grid were then generated and, with white noise of various degree added, served as a simulated SPATE output. This set of data was then used in the inverse problem where the coefficients a_k were estimated and the resulting stress components compared to those obtained in the direct problem.

3.1 Solving for γ

In order to solve either the direct or inverse problem, the solution to eqn (2.4) must firstly be sought. Because of its non-algebraic nature, a numerical algorithm using a Newton–Raphson scheme was used. The asymptotic form

$$\lim_{k \to \infty} \gamma_k = \left(\frac{3\pi}{4} + k\pi\right) + i\frac{\ln(4k+3)\pi}{2} \tag{3.1}$$

was used to generate initial estimates for the iterative solution procedure. This and all subsequent computations were done on an ELXSI 6400 and double precision programming was used throughout.

3.2 The Direct Problem

The first step in the direct problem was to decide on a stress distribution at the boundary $x = 0$. Serving as a relatively severe test case, a step function of the form

$$\begin{aligned} \sigma_{xx} &= 100 \qquad -1/3 \le y \le 1/3 \\ \sigma_{xx} &= 0 \qquad \text{elsewhere} \end{aligned} \tag{3.2}$$

was chosen, where the normal stresses σ_{xx} at $x = 0$ may be expressed as

$$\begin{aligned} \sigma_{xx} = a_o &+ \sum_{k=1}^{N} a_k\{(4\gamma_k^3 \tan\gamma_k + 8\gamma_k^2)\cos 2\gamma_k y - 8\gamma_k^3 y \sin 2\gamma_k y\} \\ &+ \sum_{k=1}^{N} \overline{a}_k\{(4\overline{\gamma}_k^3 \tan\overline{\gamma}_k + 8\overline{\gamma}_k^2)\cos 2\overline{\gamma}_k y - 8\overline{\gamma}_k^3 y \sin 2\overline{\gamma}_k y\}, \end{aligned} \tag{3.3}$$

where N is sufficiently large to represent the function expressed by eqns (3.2).

The coefficients a_k were then solved by matching the first N Fourier components of both sides of eqn (3.3). It was found that $N = 15$ was adequate to represent the required step function.

A regular grid system of 241 × 121 points was used to cover the region $0 \leq x \leq 2$ and the bulk stress at each grid point was generated using the truncated form of eqn (2.6). Random errors (up to ±5 units) were then added to the data to form a simulated SPATE output S^E. Contours of the generated bulk stress and the simulated SPATE output S^E (over the region $0 \leq x \leq 1$) are shown in Fig. 1.

3.3 The Inverse Problem

As mentioned earlier, the inverse problem involves the estimation of the coefficients a_k given a set of bulk stress data S^E. This at first appears straightforward and a least squares approach seemed appropriate for handling the noise. However, problems can arise due to under-parameterisation (the under-estimation of the number of terms necessary to represent the solution) as well as poor conditioning of the least squares matrix. These problems, and the suggested remedies, are discussed in the following.

The bulk stress may be rewritten in the form

$$\begin{aligned} S(x,y) = a_o &+ \sum_{k=1}^{N} b_{2k-1}\left(e^{-2\gamma_k x}\cos 2\gamma_k y + e^{-2\bar{\gamma}_k x}\cos 2\bar{\gamma}_k y\right) \\ &+ i\sum_{k=1}^{N} b_{2k}\left(e^{-2\gamma_k x}\cos 2\gamma_k y - e^{-2\bar{\gamma}_k x}\cos 2\bar{\gamma}_k y\right), \end{aligned} \tag{3.4}$$

where $b_{2k-1} + ib_{2k} = 8\gamma_k^2 a_k$.

The least squares problem is to find $\mathbf{b}$ such that

$$\sum_D \left[S^E(x,y) - \mathbf{b}^T \Psi(x,y)\right]^2$$

is minimised, and where

$$\begin{aligned} \mathbf{b}^T &= [a_o, b_1, b_2, \ldots, b_{2N}], \\ \Psi^T &= [\psi_o, \psi_1, \psi_2, \ldots, \psi_{2N}], \end{aligned} \tag{3.5}$$

in which

$$\begin{aligned}\psi_{2k-1}(x,y) &= e^{-2\gamma_k x}\cos 2\gamma_k y + e^{-2\overline{\gamma}_k x}\cos 2\overline{\gamma}_k y\\ \psi_{2k}(x,y) &= i\left(e^{-2\gamma_k x}\cos 2\gamma_k y - e^{-2\overline{\gamma}_k x}\cos 2\overline{\gamma}_k y\right),\end{aligned} \tag{3.6}$$

and D represent the rectangular array of grid points.

The least squares problem gives rise to the so called "normal equations"

$$\mathbf{L}\,\mathbf{b} = \mathbf{r}, \tag{3.7}$$

in which

$$\begin{aligned}L_{ij} &= \sum \psi_i(x,y)\psi_j(x,y),\\ \mathbf{r}^T &= [r_0, r_1, r_2, \ldots, r_{2N}],\end{aligned} \tag{3.8}$$

where

$$r_i = \sum S^E(x,y)\psi_i(x,y)$$

The discrete least squares problem suffers from the loss of precision due to the subtraction of two similarly valued numbers of finite word-length. If the sampling rate is sufficiently high or grid spacing is sufficiently small, then all sums may be replaced by integrals with an error proportional to the square of the grid spacing. This leads to a procedure known as Continuous Least Squares where, by performing the integrations, it may be shown that the elements of the symmetric matrix $\mathbf{L}$ are given by

$$\begin{aligned}L(1,1) &= \ell\\ L(1,2k) &= Real\left\{\frac{\sin\gamma_k}{\gamma_k^2}(1-e^{-2\gamma_k \ell})\right\},\\ L(1,2k+1) &= -Im\left\{\frac{\sin\gamma_k}{\gamma_k^2}(1-e^{-2\gamma_k \ell})\right\},\end{aligned} \tag{3.9}$$

and the remaining terms are more easily expressed in terms of the supplementary function $F(\gamma_m, \gamma_n)$ such that

$$L(2m,2n) = F(\gamma_m,\gamma_n) + F(\gamma_m,\overline{\gamma}_n) + F(\overline{\gamma}_m,\gamma_n) + F(\overline{\gamma}_m,\overline{\gamma}_n)$$

and

$$L(2m+1,2n+1) = -F(\gamma_m,\gamma_n) + F(\gamma_m,\overline{\gamma}_n) + F(\overline{\gamma}_m,\gamma_n) - F(\overline{\gamma}_m,\overline{\gamma}_n), \tag{3.10}$$

where, for $m \neq n$,

$$F(\gamma_m, \gamma_n) = \iint_D e^{-2(\gamma_m+\gamma_n)x} \cos 2\gamma_m y \cos 2\gamma_n y \, dx dy$$
$$= \frac{(1 - e^{-2(\gamma_m+\gamma_n)\ell})}{4(\gamma_m + \gamma_n)} \left[\frac{1}{\gamma_m + \gamma_n} \sin(\gamma_m + \gamma_n) + \frac{1}{\gamma_m - \gamma_n} \sin(\gamma_m - \gamma_n) \right]. \tag{3.11}$$

Note that for $m = n$,

$$F(\gamma_m, \gamma_m) = \frac{(1 - e^{-4\gamma_m \ell})}{8\gamma_m} \left[\frac{\sin 2\gamma_m}{2\gamma_m} + 1 \right]$$
$$= 0 \qquad (\text{since } \sin 2\gamma_k + 2\gamma_k = 0). \tag{3.12}$$

The least squares matrix for the problem under consideration becomes highly ill-conditioned as the number of rows (or columns) increases beyond 7. The deterioration of the conditioning of **L** is illustrated in Table 1. Such behaviour means that the inversion of **L** on a computer with finite word-lengths may not give dependable results for the high frequency modes. This gives some idea of the maximum number of parameters which can be reliably estimated in the inverse problem. However, because these parameters can be strongly correlated, it may be necessary to include higher frequency eigenfunctions in the least squares model to avoid bias in estimating the low frequency components. To systematically determine the order of the model, a consistent order estimation scheme was adopted (see Ref. [9]) which involved the minimization of the following objective function:

$$Z = N \ln \sigma_m^2 + m \ln N, \tag{3.13}$$

where N is the total number of data points, m is the number of parameters assumed in the model, and σ_m^2 is the variance of the least squares fit. It may be shown that as $N \to \infty$, m may be determined exactly.

As m increases beyond 7, the least squares matrix may deviate from being strictly positive definite due to the poor conditioning. To overcome this, a standard technique which involves the addition of a small number ϵ to the diagonal elements of **L** was adopted (see Ref. [10]). Because a Choleski decomposition was used in the matrix solver, the value of ϵ should be of the order of the square-root of the computer truncation errors. A value of $\epsilon = 10^{-6}$ was selected to be appropriate in the current example.

Number of γ's	1	2	3	4
Number of rows in **L**	3	5	7	9
Condition number†	11	86	520	4070

† The condition number here is defined as the quotient of the largest and smallest eigenvalue of the matrix.

Table 1. Conditioning of the least squares matrix.

4. RESULTS AND DISCUSSION

The minimization of the objective function expressed by eqn (3.13) allows a systematic means of determining the number of parameters which should be included in the model. The procedure adopted was to compute Z for increasing number of γ's, and select the case which corresponds to a minimum Z. For the two noise levels considered (± 2.5 and ± 5 units), this procedure returned an estimate for m of 29 (or 14 γ's). This is in close agreement with the 15 γ's actually used to generate the simulated SPATE data. However, even though such a high order system was considered, most of the parameters were estimated with substantial errors. Table 2 shows the comparison of the estimated parameters and the actual values used in the direct problem for the maximum-noise case. It is seen that only the first 8 parameters were estimated reasonably, which is consistent with the conditioning of the least squares matrix as discussed earlier (see Table 1). Despite this, these parameters were able to be reproduce the bulk stress field with exceptional accuracy as seen in Fig. 2 which shows a comparison of the bulk stress field produced in the direct problem prior to the addition of random noise, and that obtained in the inverse problem.

The comparisons of the σ_{xx}, σ_{yy} and σ_{xy} fields are shown in Figs 3 to 6 respectively. Only the results for the ± 5 unit noise case are presented here as this scheme was found to be relatively insensitive to the random noise present, and the the results for the ± 2.5 unit noise case were essentially the same. Interestingly, it is seen that the inaccurately predicted higher order parameters tend to affect the quality of estimated individual stress components much more than that for the bulk stress field. The reason for this may be easily seen from the algebraic form of these stress fields. For example, setting $x = 0$ in eqn (2.6), and comparing this

with *eqn* (3.3), it can be seen that the stress component σ_{xx} has terms which are proportional to γ_k^3 and $\bar{\gamma}_k^3$ whilst S contains only terms in γ_k^2 and $\bar{\gamma}_k^2$. Therefore, as k (and hence γ_k and $\bar{\gamma}_k$) becomes larger, *errors in* a_k would become more and more visible on stres components. Fortunately though, the higher order parameters are associated with terms which decay rapidly in the x-direction, and as shown in these figures, the spurious stresses are confined to only a small region on the loaded edge. For the bulk of the region under consideration, the inverse scheme was able to determine all three components of stresses accurately.

k	b_k (Direct)	b_k (Inverse)
1	33.3	33.3
2	48.7	48.5
3	-4.13	-3.96
4	35.2	34.7
5	-3.70	-2.44
6	7.07	7.00
7	-6.18	-4.17
8	-11.9	-12.1
9	-2.71	-0.386
10	-12.8	-9.62
11	1.88	2.77
12	-3.12	0.904
13	3.93	-4.41
14	6.86	1.37
15	2.31	-5.59
16	8.07	3.69
17	-1.26	4.32
18	2.04	5.16
19	-3.01	0.733
20	-4.88	-5.81
21	-1.96	-0.742
22	-5.93	0.167
23	1.00	3.34
24	-1.55	8.13
25	2.42	-13.3
26	3.84	-2.11
27	1.83	-16.9
28	4.74	-2.74
29	-1.13	-3.62
30	0.748	-
31	-1.30	-

Table 2. Comparison of the parameters used in generating S and those obtained in the inverse problem.

5. CONCLUSION

Whilst isopachic data such as those obtained in a thermoelastic stress analysis alone are not sufficient for individual stress components to be deduced, the corresponding stress field cannot be chosen arbitrarily. This is because a valid stress field must satisfy the conditions of equilibrium as well as the imposed boundary conditions. It has been demonstrated that by making use of these conditions, a least squares scheme can be devised to identify the stress components in a two dimensional body. For the case considered, the scheme was found to be relatively insensitive to random noise, although due to ill-conditioning of the least squares matrix, the high frequency components of stresses were not able to be resolved. However, these high frequency components of stresses dissipate extremely quickly in accordance with St. Venant's principle, and the stress components in the greater part of the region under consideration can be determined successfully.

For the purpose of demonstrating such a combined experimental-analytical stress analysis technique, the chosen example was a rather simple one. In practice, for a component of arbitrary geometry, the problem becomes much more difficult and resorting to the analytical solution may be impractical. In such a case, there is scope for adopting this least squares approach in a finite elements formulation. The viability of this combined experimental-finite elements technique is currently *under investigation.*

ACKNOWLEDGEMENT

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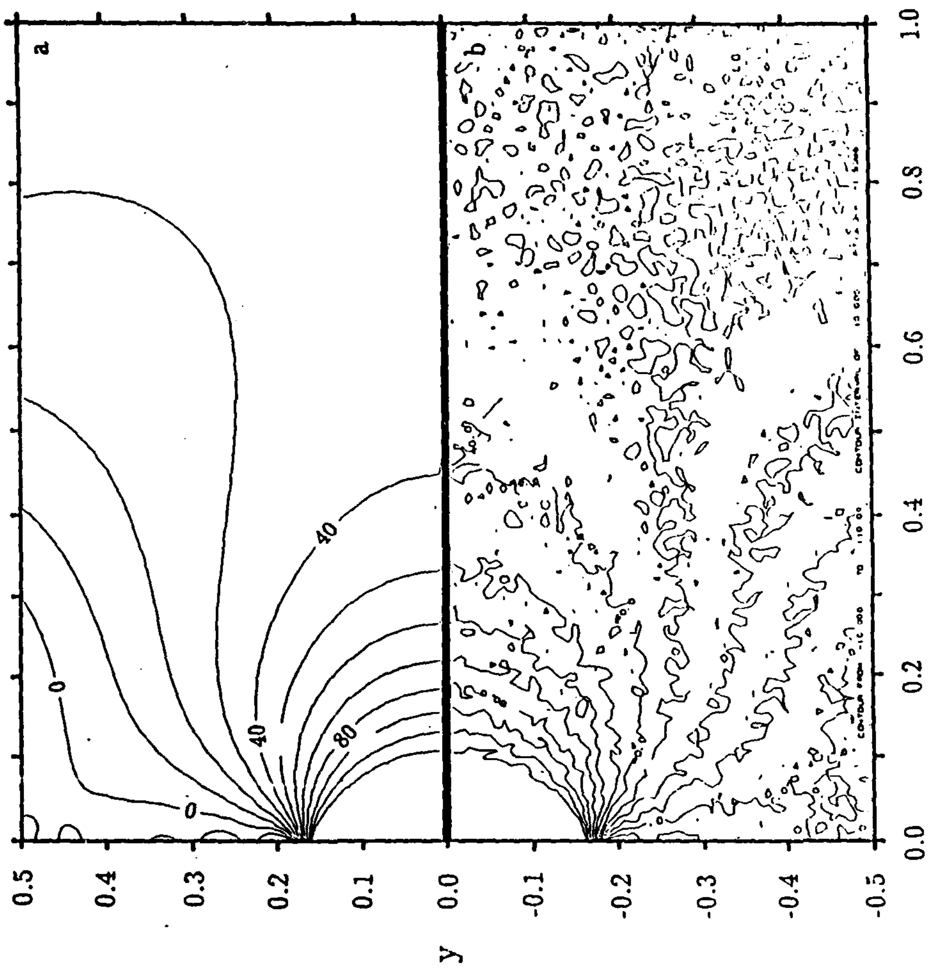

Figure 1. Contours of bulk stress data from -10 to 110 on intervals of 10; a) generated by the direct problem, b) with random noise of ±5 (max.) added. The data presented in b) were used as input data for the inverse problem.

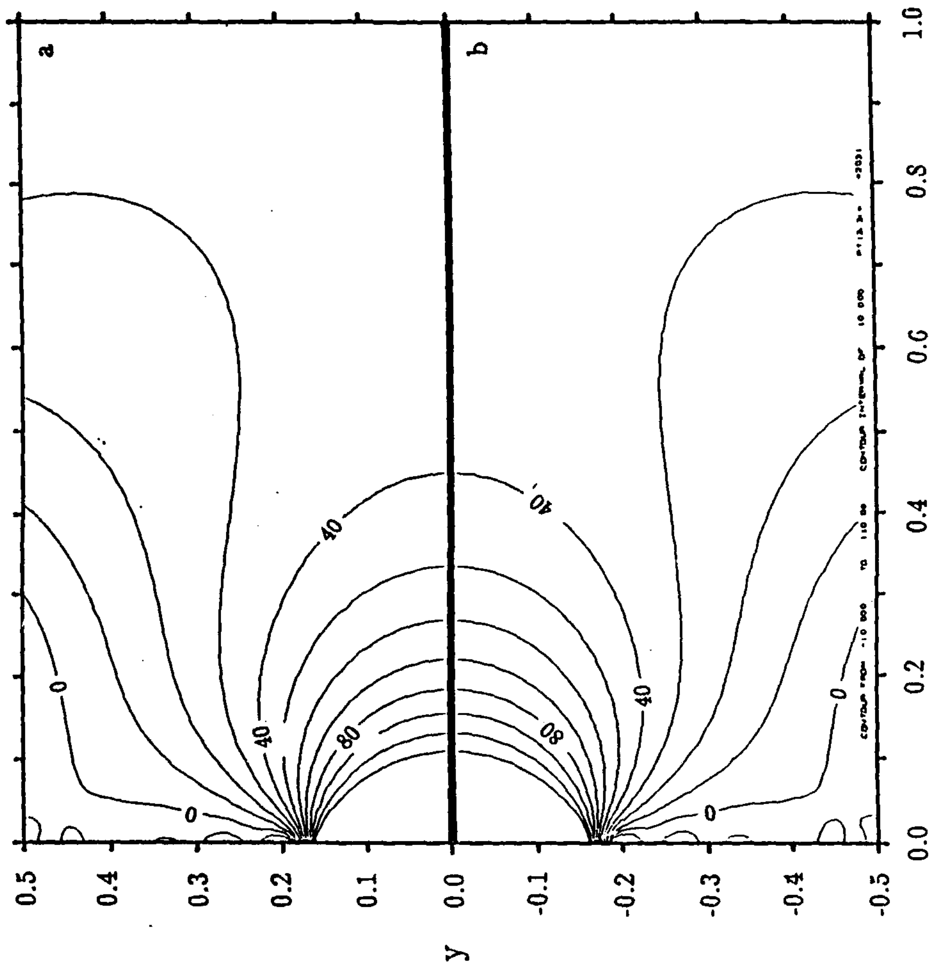

Figure 2. Contours of bulk stress from -10 to 110 on intervals of 10; a) generated by the direct problem, b) derived from the inverse problem.

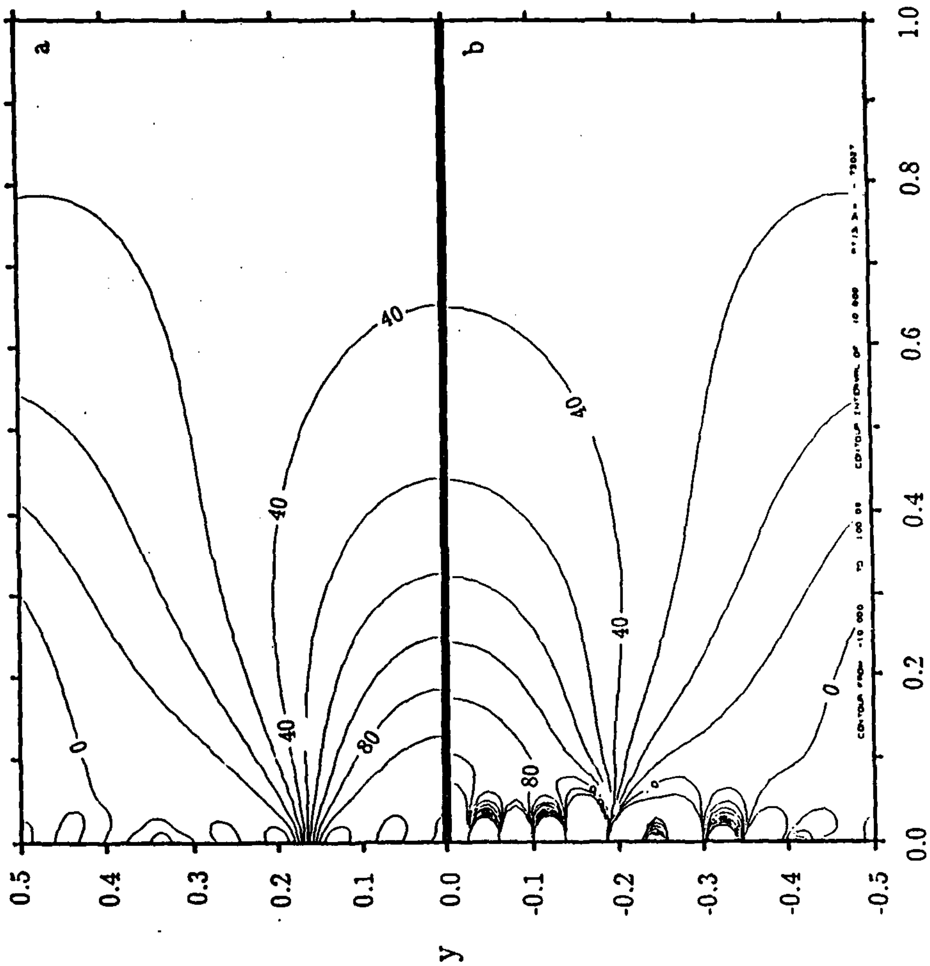

Figure 3. Contours of σ_{xx} from -10 to 100 on intervals of 10; a) generated by the direct problem, b) derived from the inverse problem.

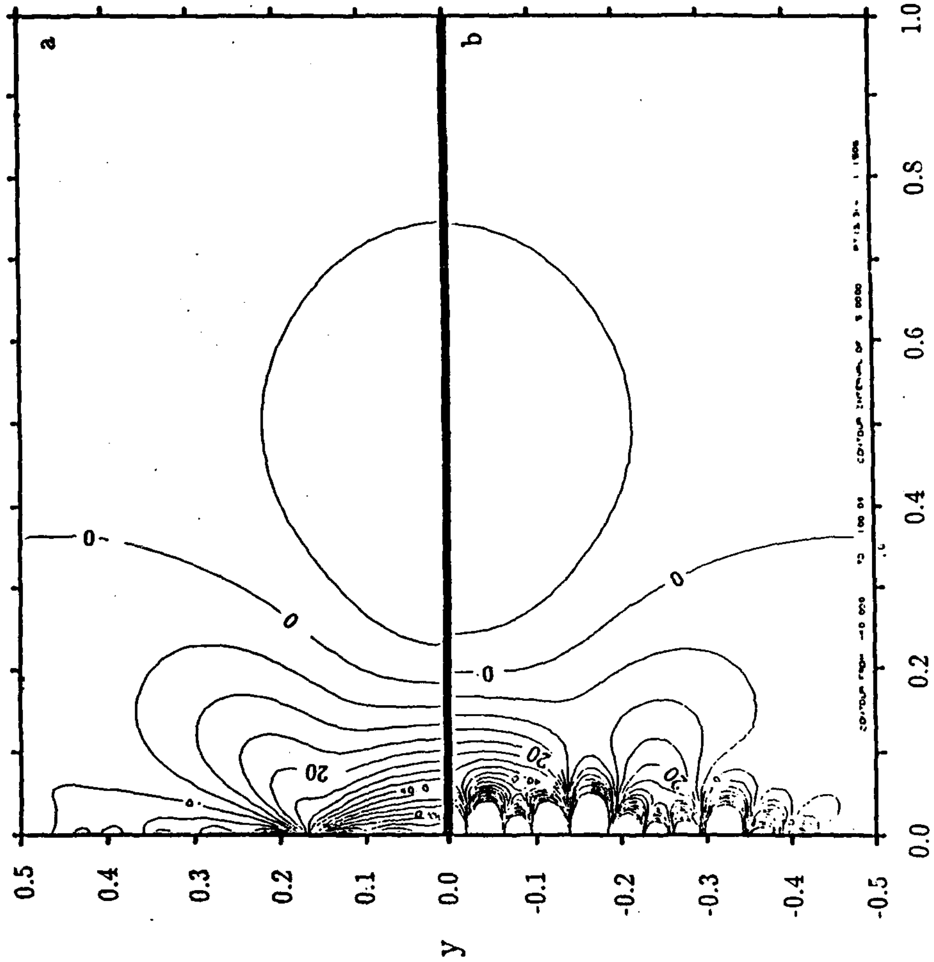

Figure 4. Contours of σ_{yy} from -40 to 100 on intervals of 5; a) generated by the direct problem, b) derived from the inverse problem.

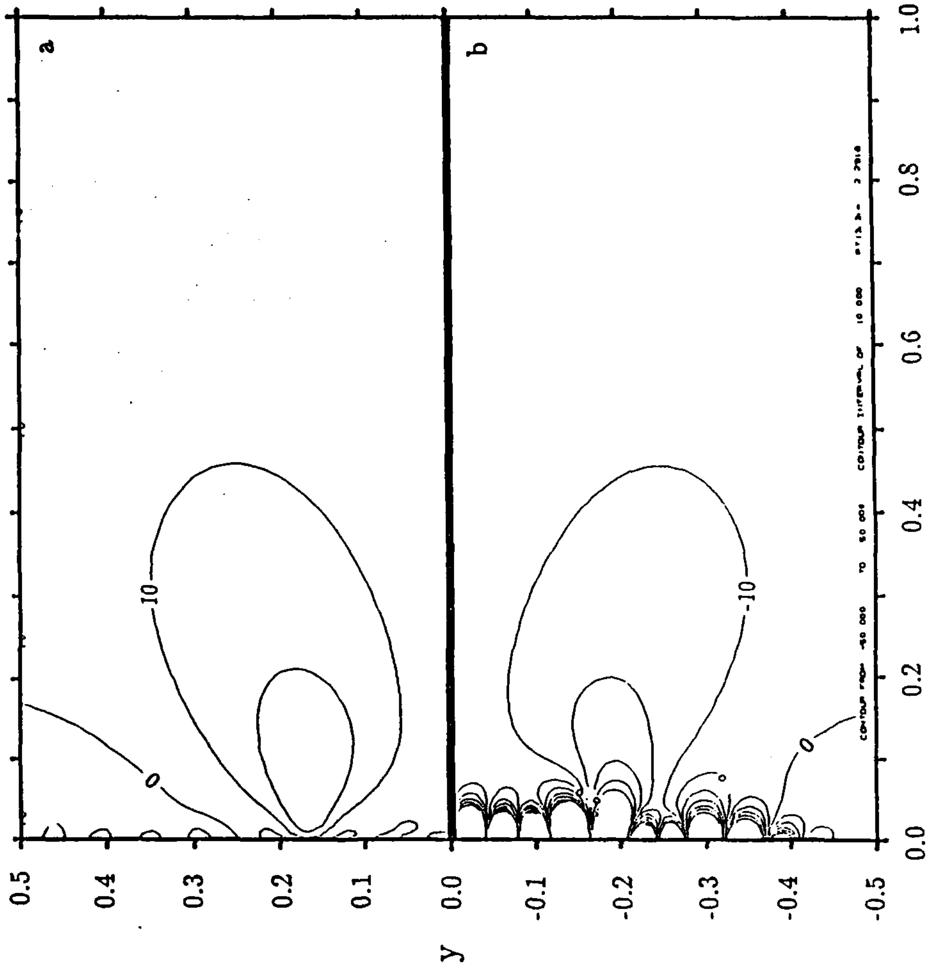

Figure 5. Contours of σ_{xy} from -50 to 50 on intervals of 10; a) generated by the direct problem, b) derived from the inverse problem.

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16. ABSTRACT

This paper presents a method for decomposing bulk stress data into individual stress components. This has applications in the field of thermoelastic stress analysis where the raw data are related only to the sum of the principal stresses (referred to as bulk stress). By considering equilibrium, and with some knowledge of the form of the solution and boundary conditions, it is shown that bulk stress data for a two dimensional body may be separated into stress components by mean of a least squares method.

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16. ABSTRACT (CONT.)

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